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Accuracy Estimation of Simplified Ray-launching Analysis for Indoor Propagation Through High Lossy Wall

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1. Intruduction

Recently, in the development of advanced wireless communication systems, it is very important to understand wave propagation in complex indoor/outdoor environments. The ray-launching or SBR method [1]-[3] is one of the most useful propagation estimation tools. The procedure of the method is very simple, so it has high computational efficiency. However, in our previous reports for a simplified 2D indoor problem [2], [3], it has been found from the detailed numerical experiments that the ray-launching solution through high lossy wall shows substantial error (over 2dB). So far, it has been found out in Ref. [3] that in the conventional ray method, the attenuation effect inside high lossy wall is estimated to be smaller than that in the analytical reference solution, and it tends to be much smaller with increase of incident angle. For resolving this undesirable problem, we have introduced an easy accuracy improvement by making the path length inside the wall slightly longer [3].

This paper presents the accuracy estimation of the modified ray-launching analysis for a simple indoor model including lots of high lossy walls. It has been verified from the detailed accuracy estimation that the modified ray-launching method gives us high accurate propagation characteristics even when ray experiences multiple reflectoins and/or transmissions due to the existence of the lossy walls. Here time harmonic factor $e^{-i\omega t}$ is assumed and suppressed throughout the context.

2. Transmitted ray in simple ray-launching method

In conventional 2D ray-launching method as in Fig.1 (a), the transmitted ray component through a dielectric wall is written as

$$G_t^{(ray)} = T(\theta_{i0}) \cdot \sqrt{\frac{1}{8\pi k_0 \bar{R}}}\, e^{i(k_0 \hat{R} + \pi/4)}, \tag{1}$$

where k_0 is the wave number in free space, θ_{i0} is the incident angle, and $T(\theta_{i0})$ is the corresponding appropriate transmission coefficient, which is composed of the product of $T_{in}(\theta_{i0})$ and $T_{out}(\theta_{i0})$.

$$T_{in}(\theta_{i0}) = \frac{2\cos\theta_{i0}}{\cos\theta_{i0} + \sqrt{\varepsilon_r - \sin^2\theta_{i0}}}, \quad T_{out}(\theta_{i0}) = \frac{2\sqrt{\varepsilon_r - \sin^2\theta_{i0}}}{\sqrt{\varepsilon_r - \sin^2\theta_{i0}} + \cos\theta_{i0}}. \tag{2}$$

The optical path lengths for amplitude and phase parts in Eq.(1) are shown as

$$\bar{R} = (\rho_0^i + \rho_0^t) + \rho\sqrt{\varepsilon_r} \cdot \frac{\cos^2\theta_{i0}}{\varepsilon_r - \sin^2\theta_{i0}}, \quad \hat{R} = (\rho_0^i + \rho_0^t) + \rho\sqrt{\varepsilon_r}. \tag{3}$$

As described in Refs. [2], [3], when the wall's material has large loss, unexpected error may be observed in the numerical result by the ray-launching method. This will be fully discussed in Section 4.

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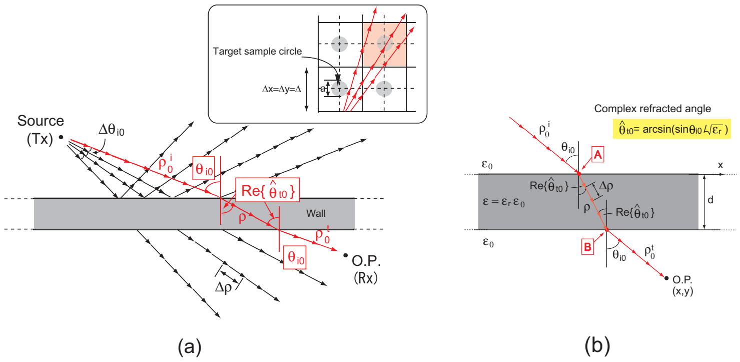


Figure 1: Launching rays through a dielectric wall

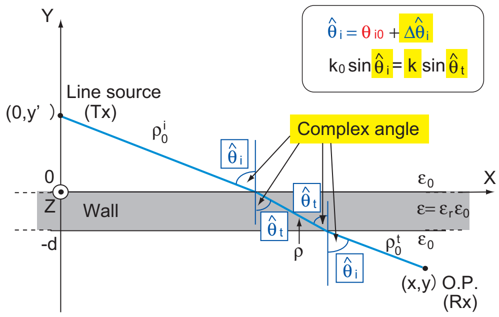


Figure 2: A line source and lossy dielectric slab

3. Analytical solution of transmitted ray for high lossy case

To find a solution to the problem in the ray-based analysis, it is important to obtain the analytical reference solution of the transmitted wave through a high lossy material wall.

As shown in Fig.2, let us now consider Green's function problem in the presence of a lossy dielectric slab, whose thickness is d and permittivity is $\varepsilon = \varepsilon_r\varepsilon_0$, $\varepsilon_r = \varepsilon_r' + i\varepsilon_r''$. According to the formulation in Ref. [2], the transmitted component can be expressed by an angular spectral w integral form, where the integrand is constituted by the product of the amplitude and the phase terms as $T(w)\cdot\exp\{q_t(w)\}$. When the slab or wall has high loss, the amplitude term $T(w)$ is no more slow varying. Then, to evaluate the proper saddle point through the SDP, the amplitude term $T(w)$ should be put into the phase term as $\exp[q_t(w) + \ln\{T(w)\}]$. For the involved integral, the saddle point $\hat{w}_s^t$ can be approximately derived as sum of conventional incident angle θ_{i0} and correction term $\Delta\hat{\theta}_i$ [3], [4] as

$$\hat{w}_s^t = \theta_{i0} + \Delta\hat{\theta}_i, \qquad \Delta\hat{\theta}_i = -\frac{1}{ik_0(\rho_0^i + \rho_0^t)}\frac{(\cos\theta_{i0} - \sqrt{\varepsilon_r - \sin^2\theta_{i0}})^2}{\varepsilon_r - \sin^2\theta_{i0}}\cdot\frac{\sin\theta_{i0}}{\cos\theta_{i0}}. \tag{4}$$

Resultantly, the spectral integral may be evaluated by the saddle point method [5] as

$$G_t = T(\theta_{i0} + \Delta\hat{\theta}_i)\cdot\sqrt{\frac{1}{8\pi k_0\bar{R}_c}}\,e^{i(k_0\hat{R}_c + \pi/4)}, \tag{5}$$

$$\bar{R}_c = \bar{R} + \frac{1}{ik_0}\cdot\frac{\cos\theta_{i0} - \sqrt{\varepsilon_r - \sin^2\theta_{i0}}}{(\varepsilon_r - \sin^2\theta_{i0})^2\cos^2\theta_{i0}}$$
$$\cdot\left\{2\sin^2\theta_{i0}\cos\theta_{i0}(1-\varepsilon_r) + (\cos\theta_{i0} - \sqrt{\varepsilon_r - \sin^2\theta_{i0}})(\varepsilon_r - \sin^2\theta_{i0})\right\}, \tag{6}$$

$$\hat{R}_c = \hat{R} - (\rho_0^i + \rho_0^t)\cdot\frac{1}{2}(\Delta\hat{\theta}_i)^2 + \rho\cdot\hat{D}, \qquad \hat{D} = \frac{\sin\theta_{i0}\cos\theta_{i0}}{\sqrt{\varepsilon_r}}\Delta\hat{\theta}_i. \tag{7}$$

4. Accuracy improvement of ray-launching method

In the conventional ray-launching procedure, one may encounter the following undesirable problems when ray passes high lossy material wall.

- For deriving the transmitted ray, the transmission point B must be first determined (See Fig.1(b)). This point B is obtained by shooting ray from the reflection point A along the direction of real refracted angle, not complex angle, even though the refracted angle $\hat{\theta}_{t0}$ becomes complex for lossy material wall [2]. $\Re e\{\hat{\theta}_{t0}\}$ has been so far utilized as an alternative real shooting direction inside the wall. However, the accuracy might not be enough high.

- As described in the previous section and Ref. [3], the transmitted ray component can be analytically derived by resolving the appropriate Green's function problem, once the observation point (Rx) and source point (Tx) are both fixed. In the analytical solution of Eq.(5), we take an undesirable fact that in addition to the transmitted angle, the incident angle must also be treated as a complex angle, $\hat{\theta}_i = \theta_{i0} + \Delta\hat{\theta}_i$. This is not familiar with the procedure of the ray-launching analysis utilizing real launching angle θ_{i0}. Furthermore, $\Delta\hat{\theta}_i$ may generate substantial errors when the loss of the slab becomes large.

To carry out accurate ray-launching indoor propagation analysis, these problems must be resolved.

So far, it has been found in the discussion of Ref. [3] that $\Delta\hat{\theta}_i$ generates the additional attenuation effect inside the high lossy wall. Hence, to compensate for the attenuation effect, instead of the conventional path length $\rho = d/\cos(\Re e\{\hat{\theta}_{t0}\})$, an alternative path length

$$\rho_c = d/\cos(|\hat{\theta}_{t0}|) \tag{8}$$

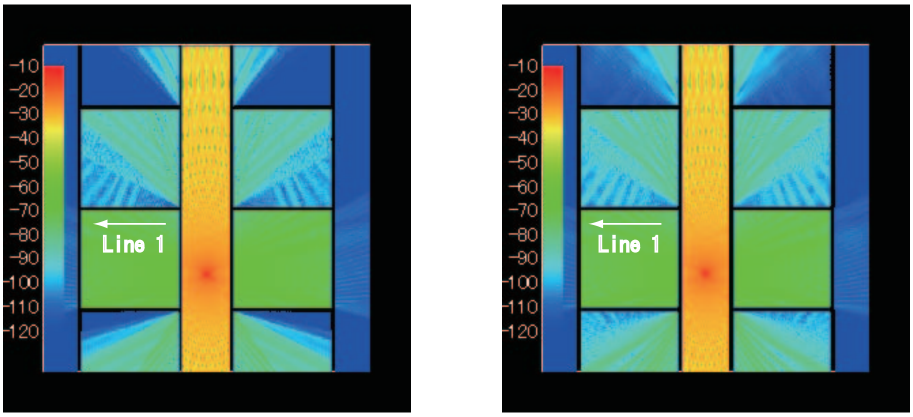
is introduced for precisely calculating the transmitted ray. This may be considered as a simple but efficient modification of the ray-launching method for high lossy case.

5. Numerical results and discussions

It has already been checked in Ref. [3] that the simple modification by Eq.(8) gives us accurate transmission characteristics through a sheet of high lossy wall. However, we do not know whether or not the modification works well under practical indoor environments including lots of high lossy walls.

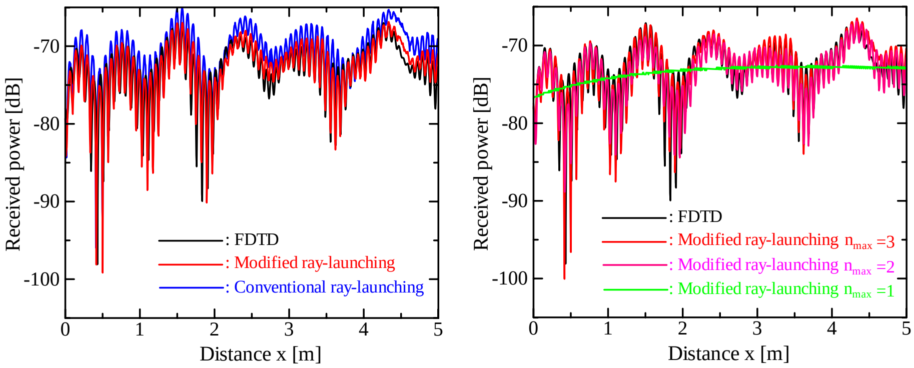
To make this uncertain point clear, let us show the numerical results of the ray-launching analysis for a simple indoor model. The analytical region of the model is 20m×20m, the geometry of each room is 6m×6m, the width of the hallway is 3m. The transmitted antenna is also located at the hallway region (6m from the bottom). Frequency is f=2.4GHz (λ = 0.125m). Each wall has 0.2m thickness, and its relative permittivity is $\varepsilon_r = 2.0 + i1.2$. Figure 3 shows the simulation result for the indoor model. Fig.3 (a) is the result of the ray-launching method modified by ρ_c, and Fig.3 (b) is that of the FDTD method [6]. In the ray-launching procedure, the square pixel size is set as Δ=0.04λ = 0.005m (The diameter of target sample circle a is 0.28λ), the shooting angle is $\Delta\theta$=0.01^o, and the total reflection/transmission number of times between/through walls is set as n_{max} = 5. Also, in the FDTD analysis of Fig.3(b), each square cell size is set as 0.005m. In comparison between the present modified ray-launching result of Fig.3 (a) and the FDTD result of Fig.3 (b), it is verified that very similar propagation tendency can be observed.

To carry out further precise accuracy estimation of the modified ray-launching method, we shall next consider the propagation feature along Line 1 in Fig.3. Figure 4 (a) shows the distance dependency of the received power along the line. In the figure, Red line shows the result of the modified ray-launching method with ρ_c, Blue is that of the conventional ray-launching method with ρ and Black is the reference FDTD result. In the figure, one can see good agreement between Red and Black lines. While, blue of the conventional ray-launching result does not show the similar propagation characteristics to the FDTD result. It is confirmed from this result that the simple modification using ρ_c realizes the accuracy improvement of the ray-launching method through high lossy walls. Finally, we shall consider the propagation characteristics for n_{max} variation. Fig.4 (b) shows the simulation result for the increase of the reflection/transmission number of times n_{max}. From this figure, one can obtain dominant indoor propagation feature for this site when n_{max} equals 3 or larger.



(a) Modified ray-launching method (b) FDTD method

Figure 3: Propagation for simple indoor model



(a) (b)

Figure 4: Received power along Line 1 in simple indoor model

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